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Progress of Ongoing NASA Lithium-Ion Cell Verification Testing for Aerospace Applications

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Abstract

A Lithium-ion Verification and Validation Program with the purpose to assess the capabilities of current aerospace lithium-ion (Li-ion) battery cells to perform in a low-earth-orbit (LEO) regime was initiated in 2002. This program involves extensive characterization and LEO life testing at ten different combinations of depth-of-discharge, temperature, and end-of-charge voltage. The test conditions selected for the life tests are defined as part of a statistically designed test matrix developed to determine the effects of operating conditions on performance and life of Li-ion cells. Results will be used to model and predict cell performance and degradation as a function of test operating conditions. Testing is being performed at the Naval Surface Warfare Center/Crane Division in Crane, Indiana. Testing was initiated in September 2004 with 40 Ah cells from Saft and 30 Ah cells from Lithion. The test program has been expanded with the addition of modules composed of 18650 cells from ABSL Power Solutions in April 2006 and the addition of 50 Ah cells from Mine Safety Appliances Co. (MSA) in June 2006. Preliminary results showing the average voltage and average available discharge capacity for the Saft and Lithion packs at the test conditions versus cycles are presented.

Introduction

Rechargeable Li-ion batteries offer a 2 to 3 times improvement in specific energy and energy density and a wider operational temperature range as compared to nickel-based battery technology. While Li-ion technology has been successfully used in both planetary rovers and on geosynchronous satellites, its long-term cycle life at low-earth-orbit (LEO) cycling conditions has not been validated. In addition, differences in battery performance caused by operating conditions, vendor-specific designs, and ongoing technology developments need to be assessed. NASA is interested in validating and verifying emerging and existing battery technologies for flight and has initiated long-term cycle life testing to assess the capabilities of current aerospace Li-ion cells to perform during long-term LEO missions. A flexible program was developed at NASA Glenn Research Center to enable assessment of technology developments as they occur and to provide information about different cell vendors and cell designs. These objectives will be achieved by testing each vendor's product at ten sets of test conditions that include combinations of three levels of temperature, end-of-charge voltage, and depth-of-discharge. The test matrix was designed using a statistical Design of Experiments.

Description of Testing

The overall test program involves acceptance and characterization testing followed by life cycle testing. Acceptance and characterization testing procedures were previously described in detail in reference 1. The charge and discharge currents used for the life cycle testing were based on the actual capacities of the cells, measured at 20 °C with a C/5 charge to 4.1 V, with a taper to C/50 and a C/2 discharge. The value of C was adjusted after each cycle to reflect the measured values. Testing was repeated until the capacity stabilized to 1 percent on subsequent cycles. The average actual capacity of the 30 Ah Lithion cells was 32.7 Ah, which is 9 percent greater than their nameplate capacity. The average actual capacity of the 40 Ah Saft cells was 45.9 Ah, which is 14.8 percent greater than their nameplate.

Test Articles and LEO Life Test Conditions

Test articles consist of forty Saft 40 Ah, HE54245, G4 chemistry cells; forty Lithion 30 Ah, INCP/28/154 cells; twenty ABSL 4S2P modules of 18650 cells; and forty MSA 50 Ah 50G01 cells. For the large cells, from Saft, Lithion, and MSA, four cells from each vendor are being tested at each combination of test conditions. For the modules, two modules are being tested at each combination of test conditions. The ten sets of conditions were statistically chosen to enable modeling of the effects of the operating conditions on cycle life and performance. Table 1 summarizes the specific test conditions for the test matrix. The superscript a indicates depth-of-discharge specific to Lithion and MSA cells and cell average conditions for the ABSL modules, and the superscript b indicates depth-of-discharge specific to Saft cells. The superscript c indicates end-of-charge voltages per cell for Saft, Lithion and ABSL, and the superscript d indicates end-of-charge voltages per cell for MSA.

TABLE 1.—MATRIX OF TEST CONDITIONS

Temperature, (°C)	End-of-charge voltage/cell, (V)	Depth of discharge, (Percent)
30	[c]4.05/[d]4.0	20
30	3.85	20
10	3.85	20
30	3.95	30
20	3.95	20
10	3.85	[a]40/[b]35
20	3.85	30
30	3.85	[a]40/[b]35
20	[c]4.05/[d]4.0	[a]40/[b]35
10	[c]4.05/ [d]4.0	30

[a]All vendors except Saft
[b]Saft
[c]All vendors except MSA
[d]MSA

Life Cycle Testing

LEO life cycle testing of the Saft and Lithion cells started in September of 2004. The ABSL modules began LEO Life cycle testing in April 2006 and acceptance and characterization testing of the MSA cells started in June of 2006.

For life cycle testing, each cell or module is charged at a rate that is 1.1 times the rate needed to return the capacity corresponding to the desired depth-of-discharge in 55 min. Cells are charged at constant current until the end-of-charge voltage is reached, then, charging continues at constant voltage for the balance of the 55 min charging period. The cell or module is discharged for 35 min at a discharge current required to achieve the desired depth of discharge. The currents are based on the average actual capacity determined as described above. Failure of a cell is defined to occur when the discharge voltage falls below 3.0 V.

Cells or modules from each vendor are randomly assigned to packs. For the large cells, each pack consists of four cells electrically connected in series with charge voltage limits being applied to the individual cells by charge control units. The charge control units, designed and built at NASA Glenn Research Center (GRC), shunt excess current around a cell once it reaches the desired end-of-charge voltage (ref. 2). To provide uniform thermal environments, the cells are mechanically restrained as

Figure 1.—Saft (lower) and Lithion (upper) cells configured in packs in test chamber.

individual cells. For the modules, each pack consists of two modules connected in parallel, which are controlled at the pack level. The packs are then randomly assigned to a set of test conditions. Testing is being performed in temperature-controlled chambers. Figure 1 shows Saft and Lithion cells configured in packs in one of the test chambers prior to the start of test.

Determination of Capacity at Specific Test Conditions

Before starting life cycle testing and periodically during life testing, the full capacity of the cells at the specific LEO test conditions is measured to 3.0 V. At 1000 cycle intervals, the LEO discharge is continued to fully discharge cells to 3.0 V. Following the full discharge, the packs are returned to LEO cycling at their specific test conditions. It typically takes between 10 and 30 cycles for the pack to stabilize.

Test Results

Life Cycle Testing

Life cycle testing of the cells was phased in by test temperature, beginning in 2004 with the packs from Lithion and Saft. As of April 30, 2006, the packs from Saft and Lithion at 20 °C had accumulated approximately 8100 cycles. The packs on life-test at 30 °C had accumulated approximately 7200 cycles and finally, the packs being cycled at 10 °C had accumulated approximately 6800 cycles. More recently, life cycle testing of modules from ABSL Power Solutions, at all three temperatures, started in April of 2006. Life cycle testing of cells from MSA will start in June of 2006. Cycle test results for the Saft and Lithion packs are presented.

Figures 2 and 3 show the average end-of-discharge voltages for the packs at each of the specific test conditions from Lithion and Saft respectively.

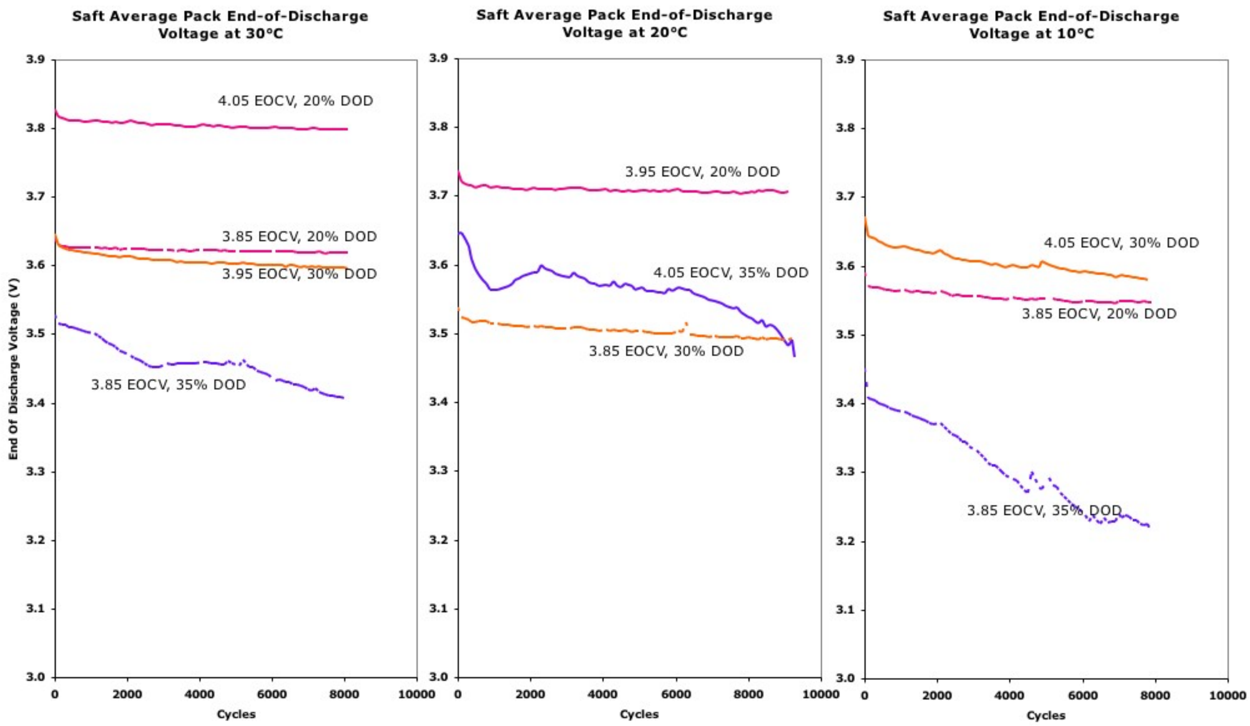

Figure 2.—Average end-of-discharge voltage versus number of cycles for Saft packs.

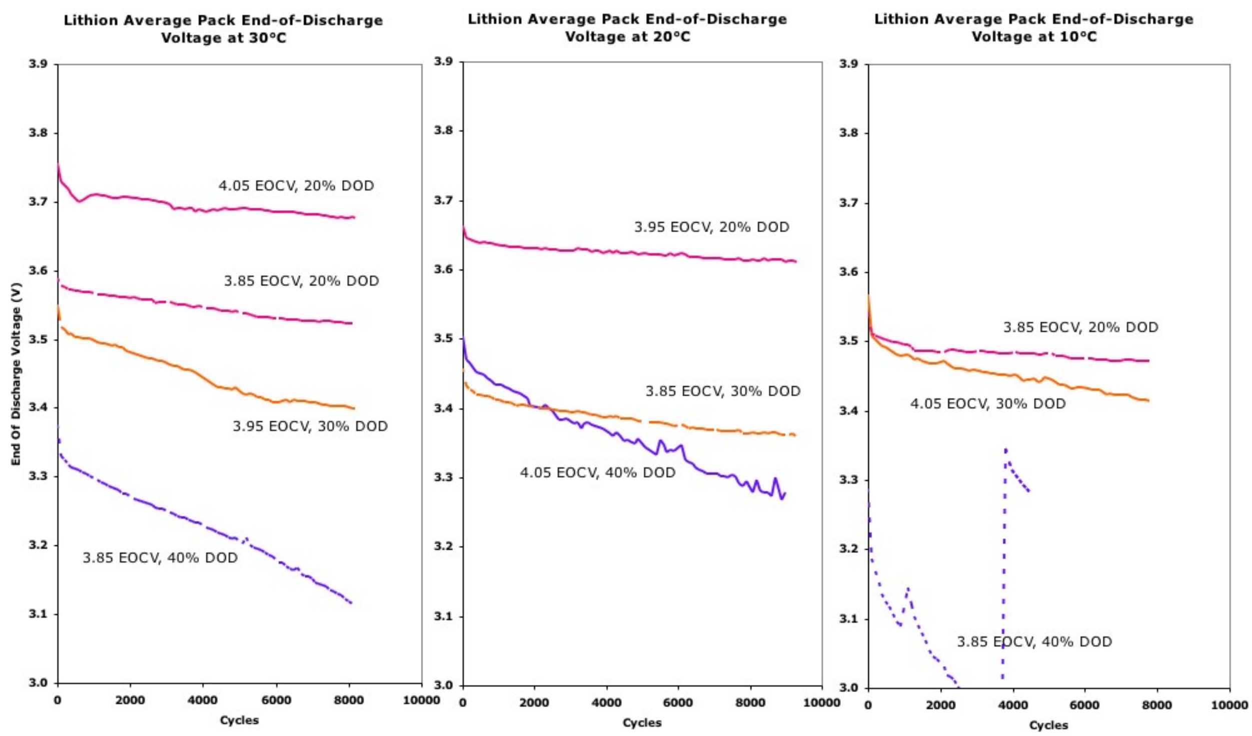

Figure 3.—Average end-of-discharge voltage versus number of cycles for Lithion packs.

Determination of Capacity at Specific Test Conditions

As a diagnostic tool, the discharge capacity of the cells at the specific test conditions is measured before life cycle testing and every 1000-cycles. Figures 4 and 5 show pack averages of these capacities for the Saft and Lithion packs respectively.

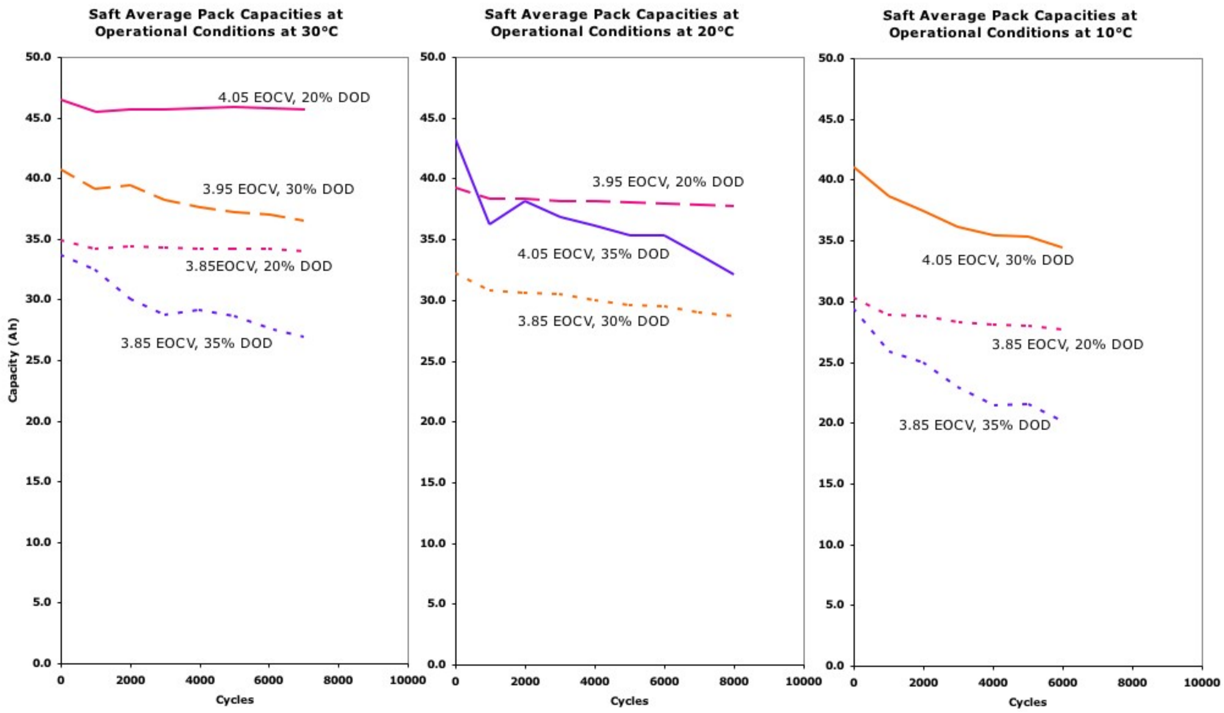

Figure 4.—Average capacity versus number of cycles at test conditions for Saft packs.

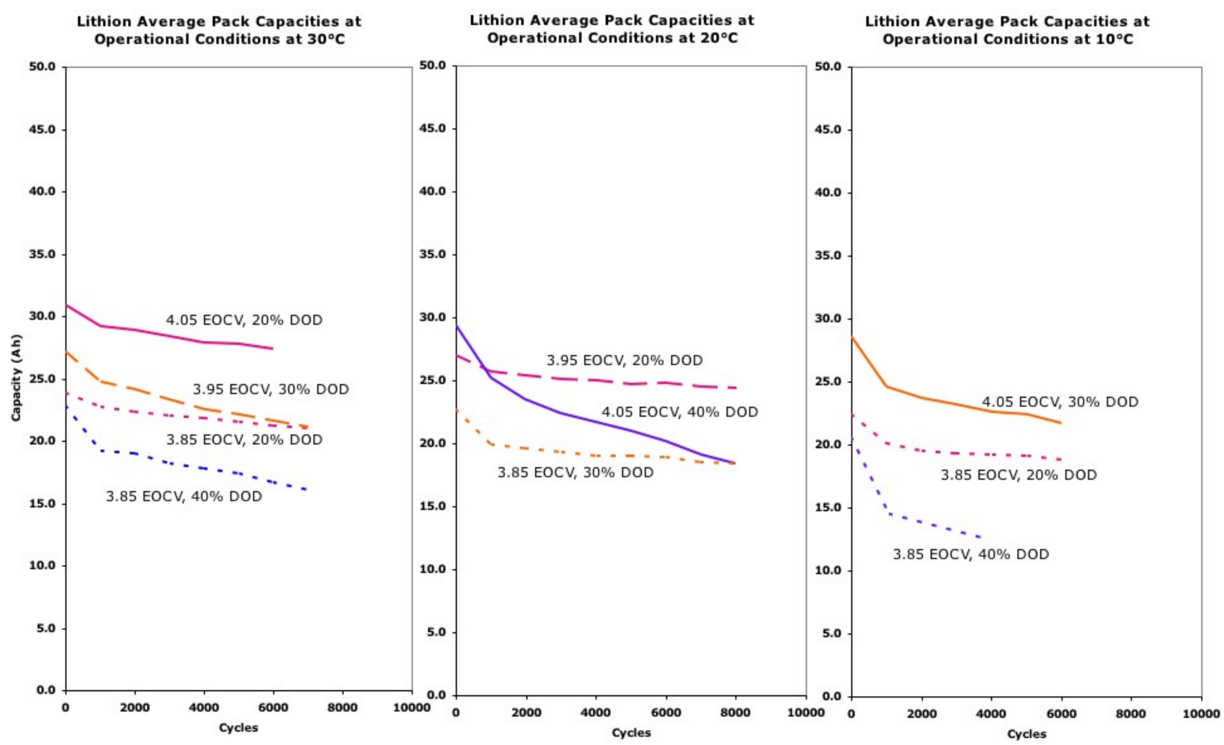

Figure 5.—Average capacity versus number of cycles at test conditions for Lithion packs.

Discussion

Failure is defined as the point where a cell's discharge voltage reaches 3.0 V. As shown in figure 3, the Lithion pack operating at 10 °C with a 3.85 V end-of-charge voltage and 40 percent depth-of-discharge failed at about 2500 cycles. This condition combines the lowest end-of-charge voltage in the matrix with the highest depth-of-discharge and the coldest temperature and thus represents the most stressful combination of parameters. The first cell in the pack failed at about 1000 cycles. After failure, the residual capacity was measured at a C/10 discharge rate. The actual capacity and self-discharge evaluation performed during the characterization phase were repeated. After failure, the actual capacities at 20 °C from 4.1 to 3.0 V ranged from 26.7 to 30 Ah as compared to 32.6 to 32.8 Ah before life cycling. The self-discharge rates were found to be 2.07 to 2.25 mV/day as compared to 0.793 to 1.243 mV/day before life cycling. After this testing, the pack was returned to LEO cycling at the same test conditions. Similar performance was observed. The end-of-charge voltage for the cells in the pack was raised to 4.05 V and the pack was returned to LEO cycling.

As shown in figures 2 and 3, the cells at higher depth-of-discharge conditions display greater decreases in end-of-discharge voltages. The cells at colder temperatures have lower starting end-of-discharge voltages. Conditions with higher depth-of-discharge or lower temperatures are also leading to greater variation in performance between the cells at a given test condition. Cells showing greater decreases in the discharge capacity available at the test conditions, as shown in figures 4 and 5, correspond to the cells showing greater declines in end-of-discharge voltage in figures 2 and 3 and also show higher cell temperatures as compared to the other cells at the same conditions. Trends in the self-discharge rate that were measured at the beginning of testing and discussed in a previous paper (ref. 1) do not correlate with trends in end-of-discharge voltage or discharge capacity at the test conditions.

These results are preliminary results at an early stage in the testing. As more data is accumulated, the effects of temperature, end-of-charge voltage, and depth-of-discharge on cycle life and performance will be statistically modeled and used for predictions of life and performance at different conditions. Due to the statistical design of the test matrix, it is difficult to perform a direct comparison of pairs of results (except for a comparison across vendors) at specific test conditions since only a few of the conditions differ in only one variable.

Future Planned Work

Life cycle testing is continuing for the products from all four vendors. The data is being evaluated to determine the impacts of the test conditions on end-of-discharge voltage trends. Equations are being developed to describe the trends that will be used to develop a model to predict cycle life.

References

1. McKissock, Barbara; Manzo, Michelle; Miller, Thomas; Reid, Concha; Bennett, William, and Gemeiner, Russel, and "Preliminary Results of NASA Lithium-Ion Cell Verification Testing for Aerospace Applications," Third International Energy Conversion Engineering Conference, August 15–18, 2005, AIAA–2005–5561, NASA/TM—2005-213995, November 2005.
2. Reid, Concha, Hand, Evan, Button, Rob, Manzo, Michelle, McKissock, Barbara, Miller, Thomas, Gemeiner, Russel, and Bennett, William, "Lithium-Ion Cell Charge Control Unit," 2004 NASA Aerospace Battery Workshop, November 16–18, 2004.

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A Lithium-ion Verification and Validation Program with the purpose to assess the capabilities of current aerospace lithium-ion (Li-ion) battery cells to perform in a low-earth-orbit (LEO) regime was initiated in 2002. This program involves extensive characterization and LEO life testing at ten different combinations of depth-of-discharge, temperature, and end-of-charge voltage. The test conditions selected for the life tests are defined as part of a statistically designed test matrix developed to determine the effects of operating conditions on performance and life of Li-ion cells. Results will be used to model and predict cell performance and degradation as a function of test operating conditions. Testing is being performed at the Naval Surface Warfare Center/Crane Division in Crane, Indiana. Testing was initiated in September 2004 with 40 Ah cells from Saft and 30 Ah cells from Lithion. The test program has been expanded with the addition of modules composed of 18650 cells from ABSL Power Solutions in April 2006 and the addition of 50 Ah cells from Mine Safety Appliances Co. (MSA) in June 2006. Preliminary results showing the average voltage and average available discharge capacity for the Saft and Lithion packs at the test conditions versus cycles are presented.

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